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**SENSITIVITY OF SUBSONIC TRANSPORT  
RANGE TO TURBOFAN ENGINE DESIGN**

by Robert W. Koenig and Laurence H. Fishbach  
Lewis Research Center  
Cleveland, Ohio  
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**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

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ABSTRACT

In support of the NASA Quiet Engine Program, the range of a DC-8-61 type airplane was calculated for turbofan engines with a variety of turbine-inlet temperatures, overall compressor pressure ratios, and bypass ratios. Appropriate values for engine weight and size and installation drag and weight were used. Two- and three-spool engines were considered. No off-design analyses were made.



# SENSITIVITY OF SUBSONIC TRANSPORT RANGE TO TURBOFAN ENGINE DESIGN

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## SUMMARY

In support of the NASA Quiet Engine Program, the range of a DC-8-61 type commercial jet transport was calculated when using turbofan engines that have design characteristics that appear promising for the quiet engine program. Engine design parameters of overall compressor pressure ratio and bypass ratio were varied in order to determine optimum values with cruise turbine-inlet temperatures of 1650, 1750, and 1850° F. Engine cycle performance was combined with appropriate engine weight, size and installation drag and weight estimates to determine the effect on range. Two- and three-spool engines were considered.

Total aircraft range was not greatly penalized by using design parameters away from optimum values for a fixed cruise turbine-inlet temperature. A 200° increase in the cruise turbine-inlet temperature at optimum bypass and compressor pressure ratios only increased the range by slightly over 3 percent. The three-spool engines were somewhat heavier than the two-spool engines; consequently, a 1 to 3 percent loss in range occurred when the three-spool engines were used.

## INTRODUCTION

The problem of noise generation by subsonic air transports has been receiving attention to a point where legislation may be enacted for noise control. Drastic solutions ranging from removing the listener from the airport area by providing an uninhabited buffer zone around the airport to launching commercial aircraft by a catapult before applying engine power for flight have been suggested. However, a more direct approach is to reduce the noise at its source--the engine.

The NASA Quiet Engine Study Program was initiated to identify the proper thermodynamic cycle characteristics and mechanical design features that will produce quieter engines for commercial jet aircraft (refs. 1 and 2). The program has pointed out the desirability of high bypass ratio for low noise.

In fact, the bypass ratios and turbine-inlet temperatures investigated in the report will produce acceptable jet noise levels which are considerably below those produced by present transport engines. This, together with the assumption that fan noise can be successfully treated, emphasizes range capability as an important criterion for engine selection. This report therefore considers the range capability of high bypass ratio engines installed in a commercial subsonic jet transport.

The engine design parameters of bypass ratio, cruise turbine-inlet temperature, and overall compressor pressure ratio were varied parametrically for two- and three-spool turbofan engines. Bypass ratio was varied from 4.5 to 6.5; turbine-inlet temperature was varied from 1650 to 1850° F; and overall compressor pressure ratio was varied from 14.7 to 24.0. The effect of the engine parameters on thermodynamic performance in conjunction with effects on bare engine weight, airflow, installed nacelle drag, and airplane weight empty were included in determining aircraft range.

The aircraft used for the study was a Douglas DC-8-61. The aircraft has four engines and is presently being used commercially as a carrier for either passengers or cargo. The vehicle was selected (ref. 3) as representative of commercial transports that would be in use during the next decade.

## ANALYSIS

### Airframe

The DC-8-61 aerodynamic and weight data were obtained from references 3 and 4. The data were modified to account for the removal of the engine, nacelles, and pylons. As the different engine designs were considered, the corresponding weight and aerodynamic corrections were added. On each flight, takeoff gross weight remained constant at 325 000 pounds. Payload and fuel reserves were also held constant. The only weights that varied were the weight of the installed engines including pylons, pods, and the weight of the useful fuel. Total range was calculated using approximate relations for ascent and descent and a Breguet cruise starting at 0.8 Mach number and 35 000 feet altitude.

### Engines

Both two- and three-spool turbofan engines were included in the study. Each engine had a single-stage fan having a

design pressure ratio of 1.55. The fan is designed for a maximum 1000 feet/second tip speed at takeoff conditions. The design values of bypass ratio were 4.5, 5.5, and 6.5; overall compressor pressure ratios were 14.7, 19.3, and 24; and the turbine-inlet temperatures were 1650, 1750, or 1850° F. All parameters are defined at the start-of-cruise point of 0.8 Mach number at 35 000 feet altitude.

Engine size was determined by requiring the installed engine thrust at the beginning of cruise (4103 pounds) to be 3 percent greater than the airplane drag. Engine diameter (fan tip diameter) was determined by assuming 30.8 pounds per second airflow (corrected to sea level static conditions) per square foot of engine frontal area. Factors such as takeoff distance and noise were not considered. However, the range of engine parameters that are studied is such that these values would be reasonable.

Uninstalled engine weight varied with number of spools (compressors--two or three) bypass ratio, overall compressor pressure ratio, turbine-inlet temperature, and engine airflow. Empirical weight relations were based on the data of reference 2 and refined follow-on engines of the quiet engine study program. These estimates included allowance for weight and volume required to treat fan noise in order to reduce it to acceptable levels. Figure 1(a) shows the effect of bypass ratio on engine weight. The weight is based on an engine that is sized to produce 4900-pound uninstalled cruise thrust, with a design fan pressure ratio of 1.55, an overall compressor pressure ratio of 24.5, and a turbine-inlet temperature of 1750° F. Figure 1(b) shows the effect of overall compressor pressure ratio on engine weight.

The weight is based on the same design parameters as figure 1(a) except bypass ratio is fixed at 5.5. The engine weight was scaled to other engine sizes by assuming weight was proportional to the ratio of airflows (required airflow/reference airflow) over the limited range of sizes required in the analysis. The reference engine airflow was 381 pounds per second at cruise conditions.

Uninstalled performance includes an ideal nozzle and inlet. Uninstalled performance was converted to installed performance to include thrust degradations resulting from inlet, nacelle, and boattail drags as well as nozzle coefficients. The duct nozzle coefficient included losses due to sound suppression material and ordinary losses. The installation effects were based on estimates from the Douglas Aircraft Division. The other installation effects included in the analysis were inlet pressure recovery loss and customer engine compressor air bleed.

Nacelle and pylon drag estimates were based on reference 4 and unpublished Douglas Aircraft Division information. The drag calculations assume a short-duct nacelle, similar to the one shown in figure 2, and accounted for skin friction, roughness, pressure and base drag on the nacelle and pylon.

Installed pylon and pod weight (pod weight includes inlet, nacelle, and nozzles less engines) was calculated from the following equation for each engine.

$$\text{Pylon and pod weight} = 9512.0 + 0.745 (\text{uninstalled engine weight} - 5125.0)$$

The constant 9512 represents a reference number for the weight of a quiet engine inlet, nacelle, and nozzle. Extra weight has been allocated for the inlet and duct nozzle, both of which are capable of some noise suppression. Also included in this constant is an effect of wing reskinning which is required for flutter considerations. The remaining part of the equation is the change in installation weight that occurs when the basic engine weight differs from the reference weight of 5125 pounds.

## RESULTS

Maximum ranges attainable with full passenger load were calculated for the various engines. The results are presented in figures 3 and 4 for two- and three-spool engines, respectively. Contours of constant range are plotted as functions of bypass ratio and overall compressor pressure ratio (fan and inner compressor). Also shown are lines of constant engine diameter. The dashed lines indicate regions where extrapolation of the data was required to generate the contours. Pertinent data for the specific engines that were analyzed are given in tables I and II for two-spool and three-spool engines, respectively. Shown are the parameters of uninstalled and installed specific fuel consumption, bare engine weight, fan tip diameter, and cruise engine airflow per engine.

A summary of the optimized maximum range cases for each turbine-inlet temperature (TIT) is given below:

Two-spool			
TIT, °F	Compressor pressure ratio	Bypass ratio	Range, st. mi.
1650	16	4.0	4255
1750	18	4.4	4306
1850	20	5.2	4355

Three-spool			
TIT, °F	Compressor pressure ratio	Bypass ratio	Range, st. mi.
1650	12	4.2	4150
1750	17	4.7	4215
1850	19	5.2	4290

At each value of TIT, the DC-8-61 using two-spool engines yielded slightly longer range than the one using three-spool engines. This is a consequence of a weight advantage for the two-spool engines, in the order of 200-400 pounds per engine. Higher TIT accompanied by increases in optimum compressor pressure ratio and bypass ratio yielded modest gains in range. A 200° F increase in the TIT benefited range by about 3 percent.

All of these optimum engines have diameters less than 75 inches and so should not present undue installation problems. Inspection of figures 3 and 4 shows that large departures from the optimum design parameters can be accepted without incurring major penalties in range. For example, at TIT of 1750° F (fig. 3(b)), a reduction of the compressor pressure ratio to 14 from 18, and raising the bypass ratio from 4.4 to 6 results in a loss in range of only 1.3 percent. However, the engine diameter would increase to 80 inches.

### CONCLUSIONS

The range of a DC-8-61 type of subsonic transport is not greatly penalized by perturbations in design bypass ratio or compressor pressure ratio away from optimum values. Increasing the cruise turbine-inlet temperature by 200° for the optimum values of bypass and compressor pressure ratio only increased the range by slightly over 3 percent. At a given value of cruise turbine-inlet temperature, a three-spool engine was slightly heavier than a two-spool engine, which results in a 1 to 3 percent loss in range. Factors such as transient operation and takeoff noise were not considered in this study.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, April 15, 1969,  
789-50-01-01-22

## REFERENCES

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2. Lewis, J. H.: Quiet Engine Definition Program; Task II Report. Pratt & Whitney Aircraft Corp., Report No. PWA 3226, March 15, 1968.
3. Anon: The Integration of Quiet Engines With Subsonic Transport Aircraft; Tasks I and II Results. McDonnell Douglas Corp., Douglas Aircraft Division, Report No. DAC-68256A, June 26, 1968.
4. Stambler, Irwin: The Big New Transports. Space/Aeronautics, August 1966, pp. 54-64.

# TABLE I.- TWO-SPOOL ENGINE DATA

[ Design fan pressure ratio, 1.55 ]

Turbine inlet temperature, 1650 °F						
Bypass ratio	Overall compressor pressure ratio	Specific fuel consumption, uninstalled	specific fuel consumption, installed	Engine weight, pounds	fan tip diameter, inches	Cruise engine airflow, lb/sec
4.5	14.7	.706	.974	4890	75.3	361
4.5	19.4	.682	1.001	5420	77.3	381
4.5	24.0	.674	1.006	5880	80.0	408
5.5	14.7	.694	.973	5190	81.9	428
5.5	19.4	.678	.986	5790	84.6	456
5.5	24.0	.683	.968	6350	88.7	502
6.5	14.7	.705	.935	5530	89.7	512
6.5	19.4	.708	.918	6230	94.3	567
6.5	24.0	.766	.825	7090	103.2	680
Turbine inlet temperature, 1750 °F						
4.5	14.7	.716	.968	4660	71.8	329
4.5	19.4	.686	1.005	5150	73.1	341
4.5	24.0	.668	1.029	5570	74.7	356
5.5	14.7	.695	.982	4930	77.5	383
5.5	19.4	.669	1.017	5450	79.1	399
5.5	24.0	.656	1.030	5900	81.2	421
6.5	14.7	.686	.980	5180	83.4	444
6.5	19.4	.666	1.000	5750	85.6	468
6.5	24.0	.664	.995	6270	88.7	502
Turbine inlet temperature, 1850 °F						
4.5	14.7	.730	.959	4480	69.1	304
4.5	19.4	.699	.997	4920	70.0	312
4.5	24.0	.676	1.039	5300	70.1	322
5.5	14.7	.704	.981	4710	74.2	351
5.5	19.4	.674	1.021	5180	75.2	361
5.5	24.0	.655	1.047	5590	76.5	374
6.5	14.7	.686	.991	4910	79.3	401
6.5	19.4	.659	1.030	5420	80.5	413
6.5	24.0	.644	1.046	5860	82.2	431

① per engine

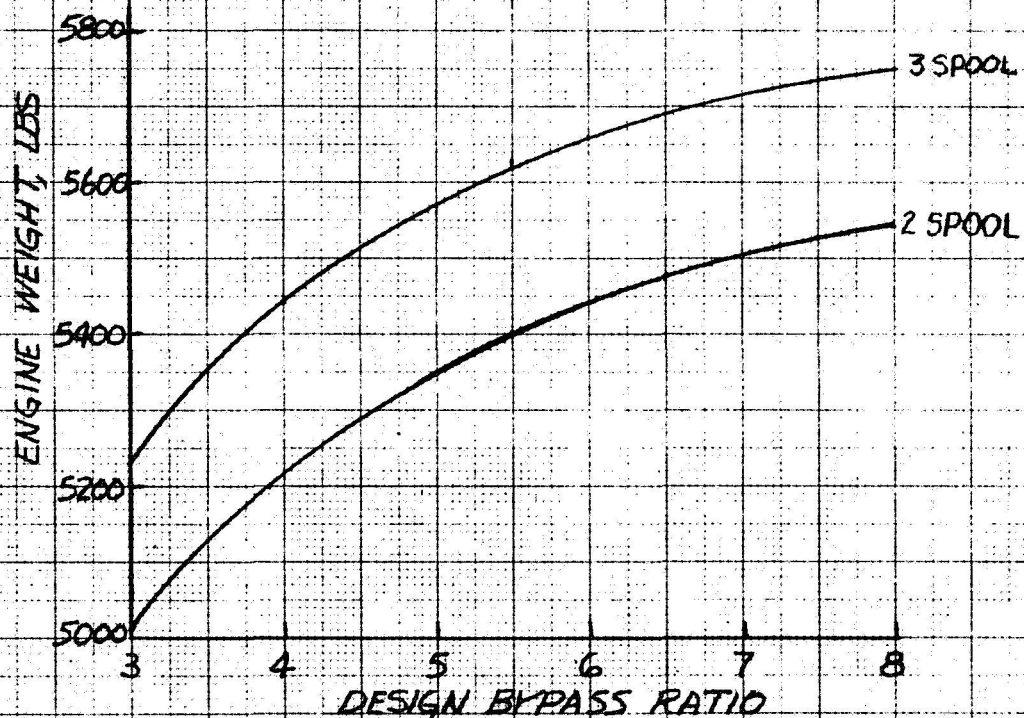
# TABLE II.-THREE SPOOL ENGINE DATA

[Design fan pressure ratio, 1.55]

Turbine inlet temperature, 1650°F						
Bypass ratio	Overall compressor pressure ratio	Specific fuel consumption, uninstalled	Specific fuel consumption, installed	Engine weight, pounds	Fan tip diameter, inches	Cruise engine thrust, lbs/sec
4.5	14.7	.706	.965	5230	75.3	361
4.5	19.4	.682	1.001	5790	77.3	381
4.5	24.0	.674	1.006	6270	80.0	408
5.5	14.7	.694	.972	5560	81.9	428
5.5	19.4	.678	.987	6170	84.6	456
5.5	24.0	.683	.968	6750	88.7	502
6.5	14.7	.705	.936	5900	89.7	512
6.5	19.4	.708	.918	6640	94.3	567
6.5	24.0	.766	.825	7520	103.3	682
Turbine inlet temperature, 1750°F						
4.5	14.7	.716	.968	4930	71.8	329
4.5	19.4	.686	1.005	5420	73.1	341
4.5	24.0	.668	1.030	5830	74.7	356
5.5	14.7	.695	.985	5180	77.5	383
5.5	19.4	.669	1.018	5720	79.1	398
5.5	24.0	.656	1.031	6200	81.2	421
6.5	14.7	.686	.980	5450	83.4	444
6.5	19.4	.666	1.002	6040	85.6	468
6.5	24.0	.664	.997	6560	88.7	502
Turbine inlet temperature, 1850°F						
4.5	14.7	.730	.958	4660	69.1	304
4.5	19.4	.699	.998	5120	70.0	312
4.5	24.0	.676	1.040	5500	71.0	322
5.5	14.7	.704	.980	4900	74.2	351
5.5	19.4	.674	1.021	5370	75.2	361
5.5	24.0	.655	1.046	5780	76.5	373
6.5	14.7	.686	.991	5100	79.3	401
6.5	19.4	.659	1.029	5610	80.5	412
6.5	24.0	.644	1.046	6060	82.2	431

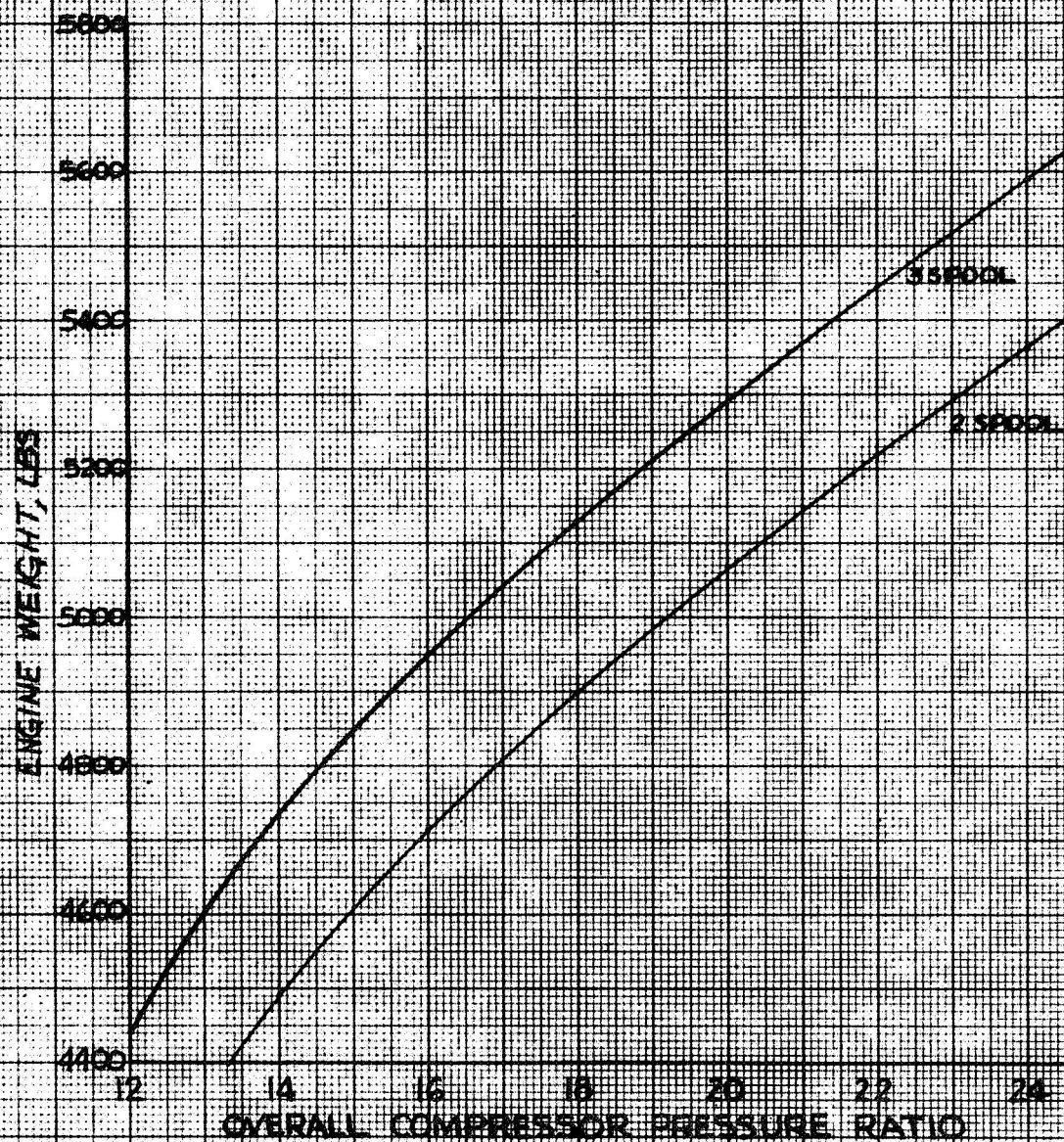
① per engine





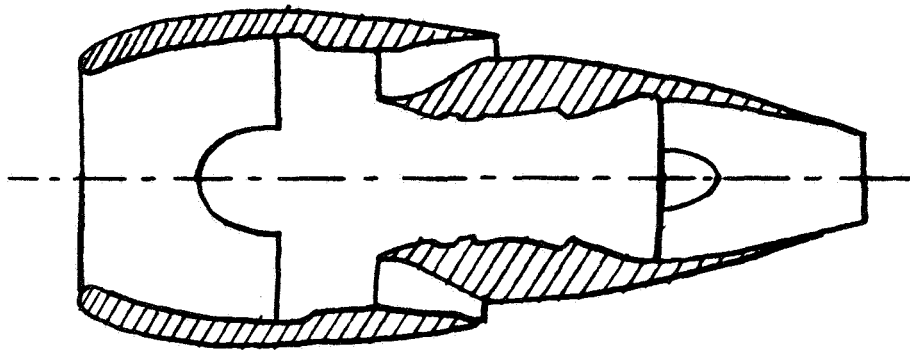
(a) EFFECT OF BYPASS RATIO; 24.5 OVERALL COMPRESSOR PRESSURE RATIO.

FIG. 1 TURBOFAN ENGINE WEIGHT BASED ON 4900 LB UNINSTALLED CRUISE THRUST, 1750 °F TURBINE INLET TEMPERATURE.



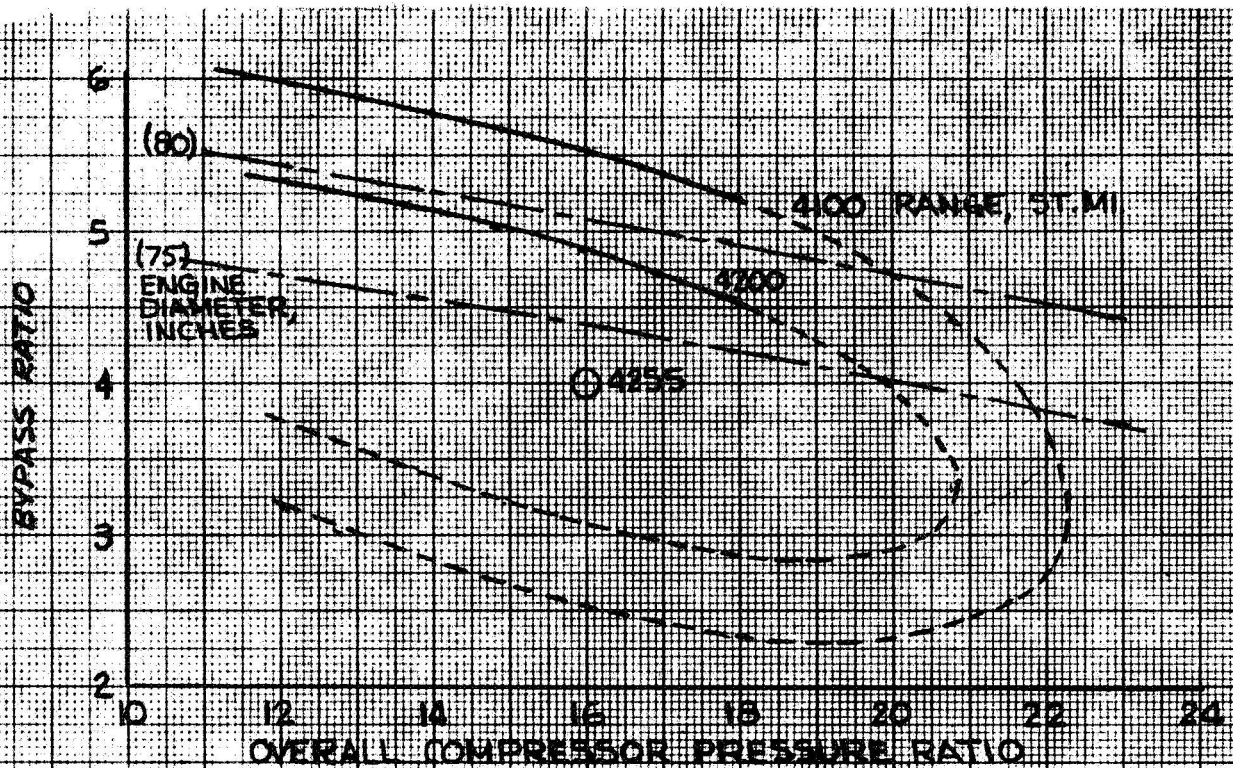
(b) EFFECT OF OVERALL COMPRESSOR PRESSURE RATIO;  
5.5 BYPASS RATIO

FIG 1 (CONCLUDED)

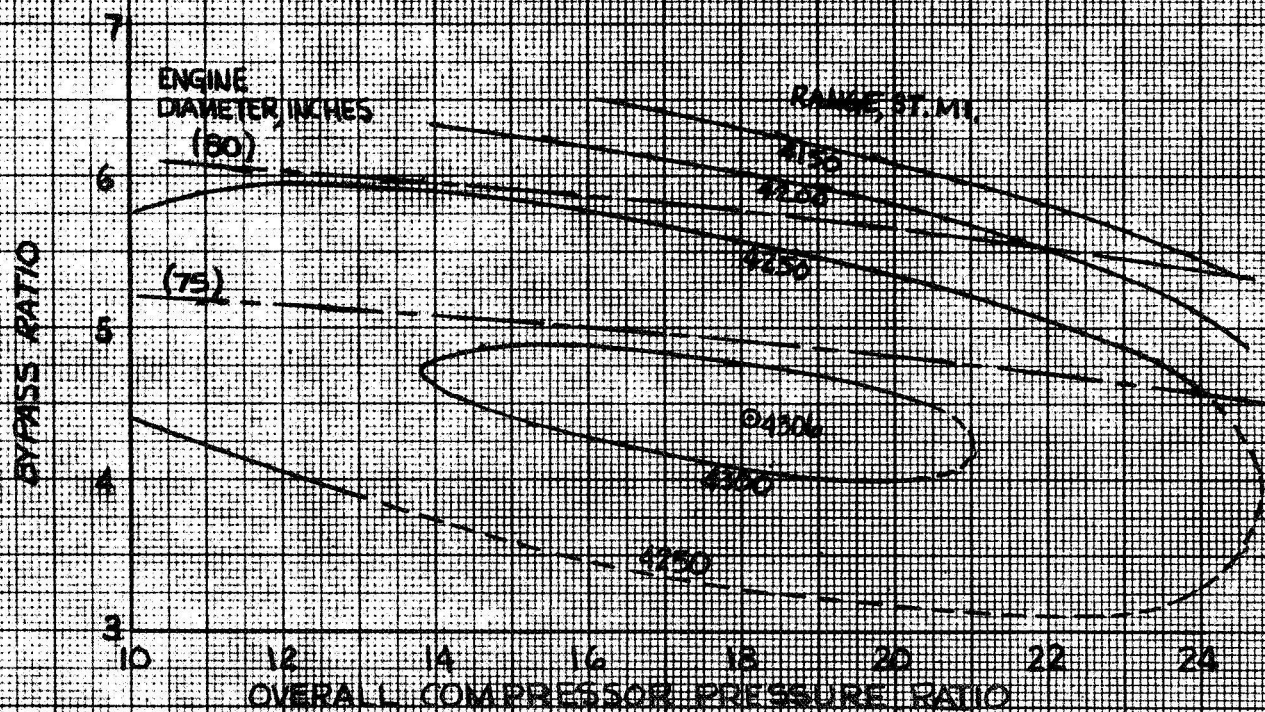


*FIG 2 - TYPICAL SHORT DUCT NACELLE INSTALLATION*





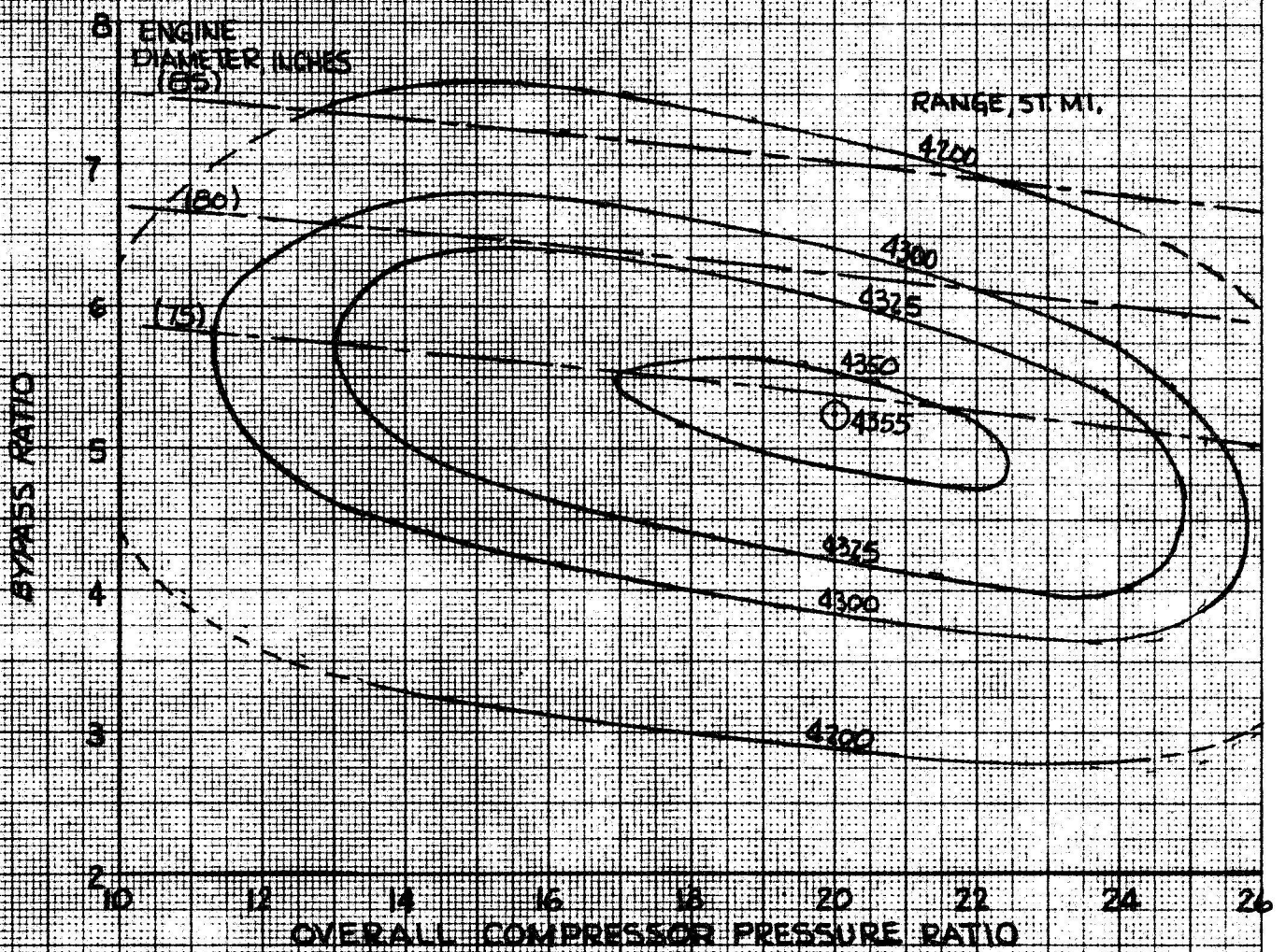
(a) TURBINE-INLET TEMPERATURE, 1650°F



(b) TURBINE-INLET TEMPERATURE, 1750°F

FIG. 3 - AIRPLANE PERFORMANCE WITH TWO-SPOOL TURBOFAN ENGINES. FAN PRESSURE RATIO, 1.55

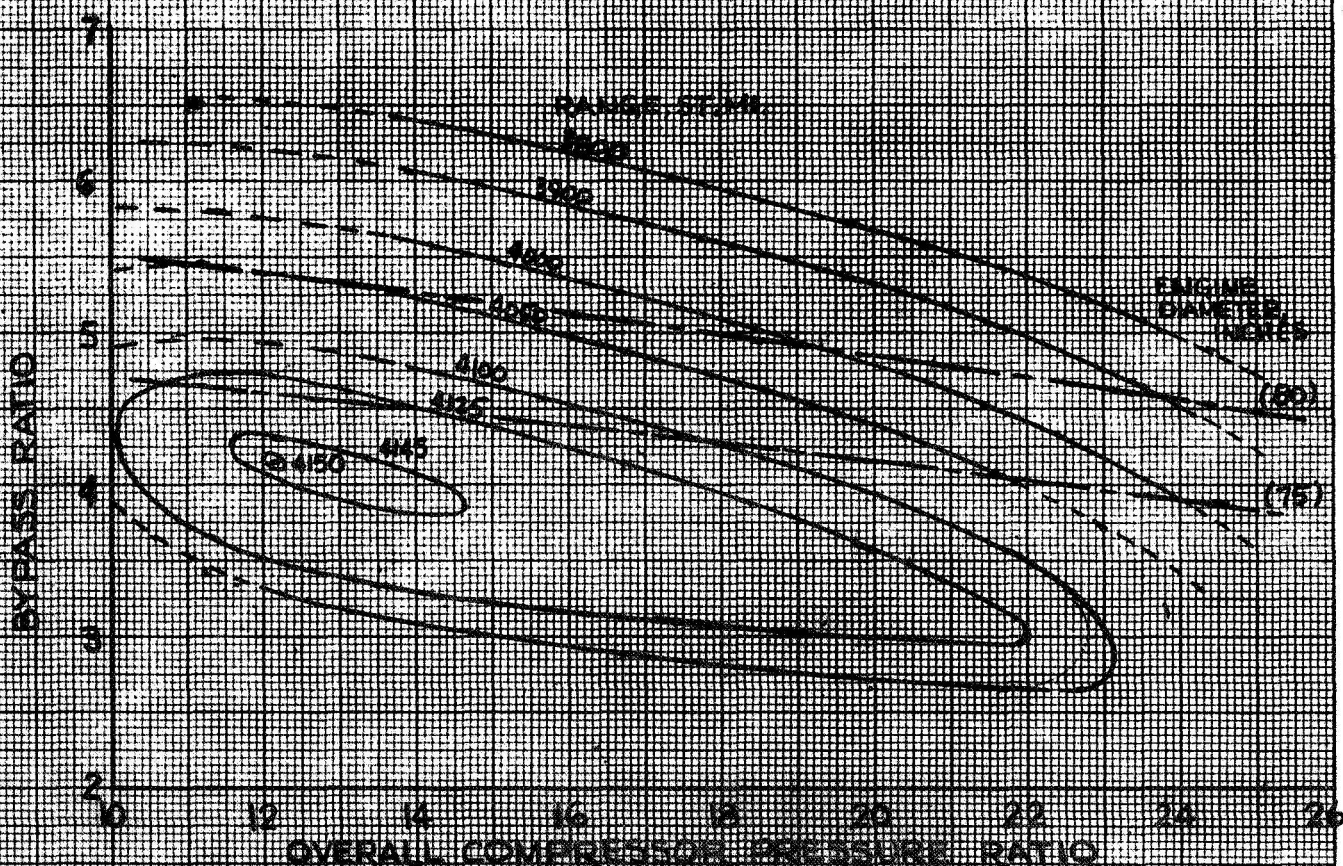




(c) TURBINE-INLET TEMPERATURE, 1850°F

FIG. 3- (concluded)

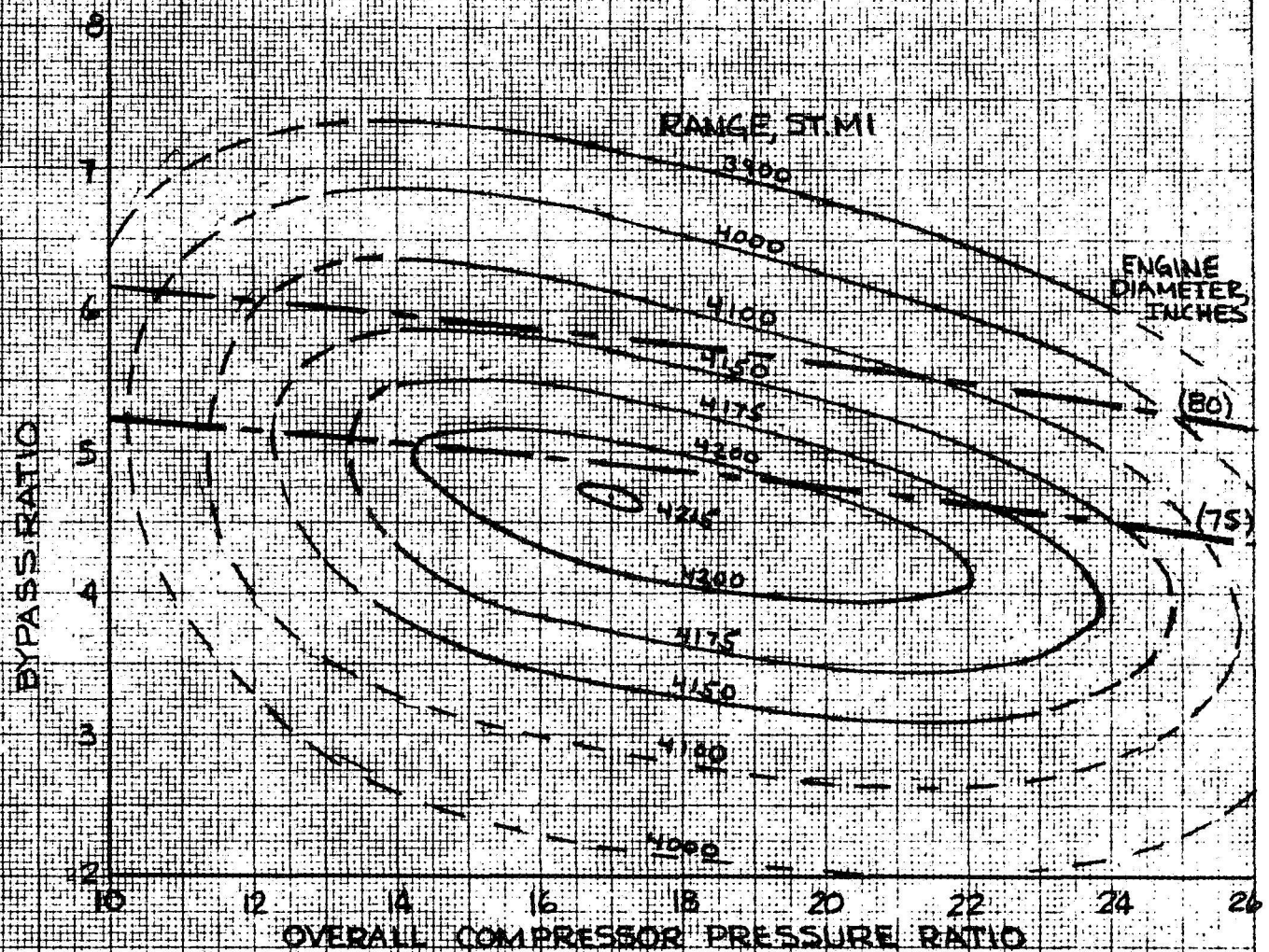




(a) TURBINE-INLET TEMPERATURE, 1650°F

FIG 4- AIRPLANE PERFORMANCE WITH THREE-SPOOL TURBOFAN ENGINE. FAN PRESSURE RATIO, 1.55

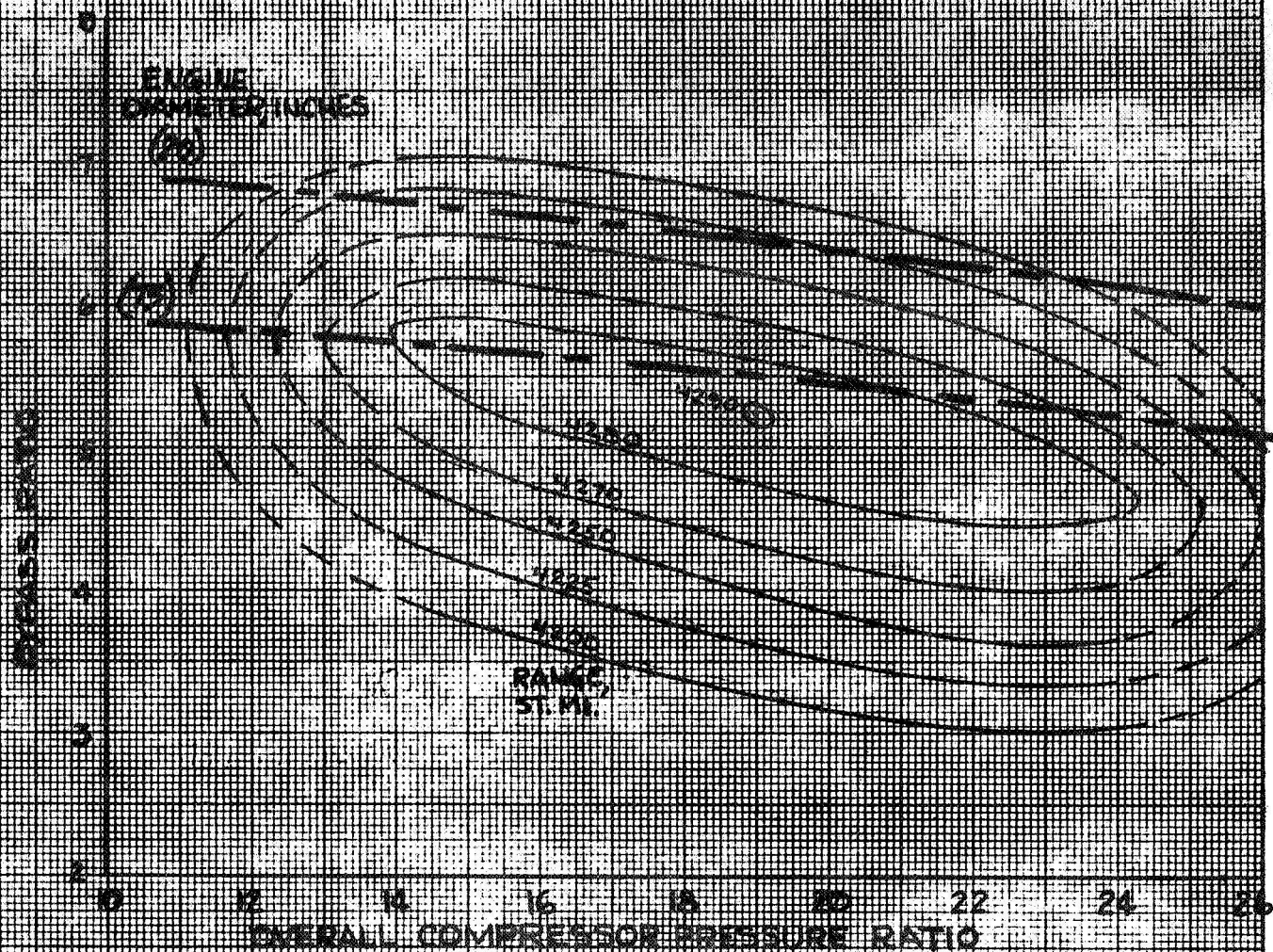




(b) TURBINE-INLET TEMPERATURE, 1750°F

FIG. 4, - (CONTINUED)





(C) TURBINE INLET TEMPERATURE, 1850 °F

FIG. 4 - (CONCLUDED)